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Radioactive Danger

1.1. Introduction

The concept of the atom[1], the unbreakable unit of matter, was first put forward over 24 centuries ago by Leucippus (460–370 BC) and his disciple Democritus (460–370 BC). That atoms are the ultimate constituents of matter was cast into doubt with the discovery of radioactivity in 1896 by Henri Becquerel (1852–1908), followed by the Curies' work on uranium ore processing residues. In 1900, Marie Curie (1867–1934) wrote: "radioactive matter is not an ordinary chemical state; atoms are not constituted in a stable state, since particles smaller than the atom are radiated. The chemically indivisible atom **is divisible here**, and the **sub-atoms** are in motion".

In 1903, Frédéric Soddy (1877–1956) and William Ramsay (1852–1916) enclosed a 20 mg sample of radium bromide in a closed container, and after a few months discovered that it contained helium. This proved that the radium atom had split by expelling a helium atom. The residue is necessarily another element [FER 06, p. 50]. In her thesis, Marie Curie shows that radioactive decay (known as the law of deactivation) is an exponential law [CUR 04, pp. 118, 162]. She underlined the importance of Soddy and Ramsay's discovery of helium and confirmed that radium and thorium emanations[2] do not seem to be altered by various energetic chemical agents, and for this reason, Rutherford and Soddy assimilated them to gases of the argon family.

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1 The word atom is borrowed from ancient Greek, derived from **tomos** meaning to *cut*, *divide*, with the prefix -a- privative, giving **atomos** the meaning *unbreakable* or *uncut*.

2 These are radon-222 (descendant of radium-226) and radon-220 (descendant of thorium-232).

Several physicists began to suggest that atoms might themselves be compound objects. They also drew up structural diagrams of the atom. Jean Perrin (1870–1942), in February 1900, imagined a structure that is striking in retrospect:

> Each atom would be made up, on the one hand, of one or more masses charged with positive electricity…and on the other hand, a multitude of corpuscles, a kind of small negative planet, all the masses gravitating under the action of electrical forces and the total charge being exactly equivalent to the total positive charge, so that the atom would be electrically neutral…the negative corpuscles always appear identical to each other, whatever the chemical nature of the atom from which they are detached.

The text of his lecture was published, but Jean Perrin did not develop this luminous hypothesis and never returned to the subject.

In contrast, Rutherford (1871–1937) specified a structure on March 7, 1911, in a two-page note. His model of the atom consisted of a central electric charge concentrated in one point and surrounded by a uniform spherical distribution of electricity of opposite sign in equal quantity. In an article dated August 16, 1912, he even used the Latin word *nucleus* [FER 06, p. 92], the nucleus of the atom. However, Niels Bohr (1885–1962) reminded us that there could be no static equilibrium between the nucleus and the electrons, and that they therefore rotate (1912). The blueprint became clearer.

When moving from one element to another in Mendeleev's classification (1834–1907), a fundamental quantity increases by a constant amount. For the English physicist Henry Moseley (1887–1915), this quantity could only be the charge of the positive central nucleus. He thus discovered that what was known as the atomic number corresponded to the number of elementary charges in the atom's nucleus [FER 06, p. 96].

The dangers presented by ionizing radiation were highlighted by Henri Becquerel and Marie Curie at the very time of their discovery. In a note to the Académie des Sciences (French Academy of Sciences) in 1901, Henri Becquerel and Pierre Curie (1859–1906) [BEC 01] recount the story of the first illnesses that affected scientists working with radium, who were not yet aware of the deleterious effects of extensive exposure to ionizing radiation.

It was two German researchers, the physicist Otto Walkoff and the chemist Friedrich Giesel (1852–1927), who published their first observations in October 1900. After placing radium wrapped in a sheet of celluloid on his arm for two hours, Mr. Giesel observed a slight reddening which increased and, after three weeks, caused the skin to "inflame" and then fall off. It was the first voluntary radiodermatitis!

Pierre Curie [CUR 01] then decided to reproduce Giesel's experiment, placing a thin sheet of gutta-percha on his arm for 10 hours, on which he had deposited "radiferous barium chloride". The skin became red over an area of 6 cm^2, a burn-like redness that increased in intensity and on the 20th day turned into a sore. After 42 days, the epidermis began to reform, but 52 days later, a 1 cm^2 wound remained, with a grayish appearance, indicating deep damage to the epidermis and dermis. This was the first severe radiological burn.

Henri Becquerel's experiment was "involuntary". For around six hours, he placed a box containing a small sealed glass tube[3] that contained radiferous barium chloride in his vest pocket. Ten days later, he noticed a reddening of the tube's oblong shape on his skin at the bottom of the pocket. Three weeks after exposure, a wound formed. It closed seven weeks after exposure, leaving a scar. While this burn was being treated, a second oblong red spot appeared, opposite the other corner of his vest pocket. The vial, which had been moved in the pocket, had produced a second erythema.

The authors also recall in this note that Marie Curie, carrying for less than half an hour a small sealed glass tube containing a few centigrams[4] of "the same very active material", enclosed in a thin metal box, had "after 15 days a red stain which gave a blister similar to that of a superficial burn". Henri Becquerel and Pierre Curie concluded by noting that the duration of the alterations varies with the intensity of the active rays and the duration of the excitatory action, and that the extremities of the fingers, which have held tubes or capsules containing highly active products, become hard and sometimes very painful. In one case, the inflammation of the fingertips lasted a fortnight before the skin fell off, but the painful sensitivity had not completely disappeared after two months.

As we shall see in Chapter 10, in addition to these short-term effects, caused by high local doses and dose rates[5] of ionizing radiation, radiation-induced diseases can be caused by doses and dose rates much lower than those producing radiation burns, administered to all or part of the whole organism. These conditions often develop late in life, with latency periods measured in years or even decades.

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3 A tube 20 mm long and 4 mm in diameter [BER 07, p. 81].

4 One centigram of radiated barium chloride.

5 The dose rate represents the dose delivered per unit of time. It is expressed in grays per second (Gy/s). This is a very important unit. For practical reasons, measurements taken in the workplace are generally expressed in milligrays per hour (mGy/h).

For more than a century, our knowledge of the dangers of radioactivity has made great strides forward. Protecting people and the environment requires knowledge of the harmful effects of the different types of radiation emitted by radionuclides and by electrical ionizing radiation generators.

1.2. Radionuclides and radioelements

Chemical elements frequently have several isotopes, the majority of which are stable, while others are radioactive. Some chemical elements have a radioactive isotope, such as carbon with isotope 14 (^{14}C) or potassium with ^{40}K, while the two heaviest natural elements, uranium and thorium, produce a chain of radioactive isotopes. Natural uranium is made up of three radioactive isotopes, uranium 234 (^{234}U), uranium 235 (^{235}U) and uranium 238 (^{238}U), which are, respectively, in the following proportions: 0.0055%, 0.720% and 99.2745%, while thorium has only one nuclide, thorium 232 (^{232}Th), and is radioactive. ^{234}U is a descendant of ^{238}U, while ^{235}U is the origin of a family of descendants independent of ^{238}U. As uranium and thorium are naturally occurring chemical elements consisting only of radioactive isotopes, they are referred to as radioelements. The radioactive isotope of an element is called a radionuclide or radioisotope. Hydrogen, for example, has three isotopes, two stable (hydrogen and deuterium) and one radioactive (tritium). In the case of carbon, carbon-14 is a radionuclide, while carbons-12 and 13 are stable isotopes.

Radionuclides can be natural or artificial, i.e. created by a deliberately activated nuclear reaction (fission, neutron activation). They all have an unstable nucleus due to an excess of protons, neutrons or both. The greater their instability, the shorter their physical half-life. Eventually, they regain stability by emitting radiation that releases their excess energy. This is what characterizes radioactivity. However, when a radionuclide decays, it may not regain stability, but instead gives rise to a new radionuclide by filiation. ^{235}U and ^{238}U as well as ^{232}Th are natural radioactive families with many daughter elements. Radium-226 (^{226}Ra), discovered by Marie Curie, and uranium-234 (^{234}U) are among the 19 descendants of the ^{238}U family. The last descendant of the ^{238}U family is stable: lead-206. ^{232}Th has 11 sons, the last of which is stable: lead-208.

There are approximately 2,000 nuclides, including the current 120 elements[6] of the periodic table, and only 325 nuclides exist naturally (274 stable and 51 radioactive nuclei), the others, all unstable, being created artificially. Only 21 elements have no isotope, since they possess only one natural nuclide (^{9}Be, ^{19}F, ^{23}Na, ^{27}Al, ^{31}P, ^{45}Sc, ^{55}Mn, ^{59}Co, ^{75}As, ^{89}Y, ^{93}Nb, ^{103}Rh, ^{127}I, ^{133}Cs, ^{141}Pr, ^{159}Tb,

6 The latest, heaviest, artificially produced element (Z = 118) was named *Oganesson* in August 2016 by the International Union of Pure and Applied Chemistry, in honor of the Armenian-born Russian physicist Yuri Oganessian, a pioneer of transuranium research.

^{165}Ho, ^{169}Tm, ^{197}Au, ^{209}Bi, ^{232}Th) [SEE 81]. Xenon has nine isotopes and tin is the element with the most, with 10 natural isotopes. Technetium, with atomic number 43, and the six chemical elements between bismuth (z = 83) and thorium (z = 90) (polonium, astatine, radon, francium, radium, actinium) have no stable isotope.

Only hydrogen isotopes have been given specific names and symbols. The most abundant (99.985%) is hydrogen (^{1}H), with only one proton. Deuterium[7] (^{2}D), or "heavy" hydrogen, is only 0.015% present in the hydrogen in air. It has one proton and one neutron. Tritium (^{3}T) is the only unstable isotope, with one proton and two neutrons. In oceans, seas and surface waters, there is semi-heavy water, water (H_2O) in which a deuterium atom has replaced the hydrogen (HDO), far more abundant than heavy water (D_2O). Semi-heavy water is naturally present in water in a proportion of 0.03125%, or one molecule for every 3,200 molecules of water.

1.3. Radionuclide-related dangers

In theory, the danger from internal radionuclide contamination is threefold: chemical stress, radioactive stress and combined stress. Chemical stress is caused by stable or radioactive metal ions, which cause cellular toxicity by binding to sensitive biomolecules such as DNA or proteins, or by substituting for biologically useful elements, thus blocking various enzymes. Metals also act indirectly by causing the formation of reactive oxygen species (ROS), notably as a result of oxidation–reduction reactions.

Radiation stress has two modes of exposure, external and internal. In the case of external exposure, only high-energy, penetrating radiation will reach all biological tissues. On the contrary, in the case of low-energy radiation and internal contamination, the low penetrating power of the rays is an amplifying factor, as all their energy is deposited very locally and in a highly concentrated manner, i.e. a high linear energy transfer (LET). In addition, the dose rate can also influence damage[8], with a high dose over a short period of time having a greater effect than a low dose spread over the long term. In the latter case, detoxification and repair mechanisms[9] will be able to take effect. Damage caused by ionizing radiation can be direct (ionization of the target) or indirect (generation of ROS). Damage depends on the nature of the radiation and its energy.

7 The discovery of this hydrogen isotope was announced on December 5, 1931 by three American physicists: H. Urey, F. Brickewedde and G. Murphy of Colombia University (NY).

8 The ICRP has recognized that chronic exposure of workers to ionizing radiation is, for the same dose, half as damaging as a dose delivered at a high dose rate.

9 For example, the induction of certain proteins such as metallothionein, which bind certain elements and thus reduce their chemical toxicity.

Combined stress is due to the fact that most radioactive contaminants combine radiative and chemical effects. Furthermore, in some cases, decay of the radioactive element is accompanied by atomic transformation (transmutation), sometimes resulting in a chain of radioactive or stable descendants with their own toxicity. In most cases of radioactive contamination, there is not just one type of radionuclide, but multiple radioactive elements. These elements may or may not interact with each other. In the latter case, the effects may present three alternatives: simple addition, antagonism or synergy. Low doses of toxic substances can induce potentiation, or on the contrary, trigger adaptation.

In practice, radiative effects are far more toxic than chemical effects, as they appear at much lower concentrations. The only known exception is uranium, for which chemical toxicity outweighs radiological toxicity. The radioactive limits for uranium intake by inhalation and ingestion result from the conversion[10] of the number of milligrams of the limit values adopted for chemical toxicity, into uranium becquerels. The values in Bq/mg of natural uranium (25 Bq/mg) change if the uranium is enriched or depleted: 63 Bq/mg for uranium enriched to 3% in ^{235}U and 15 Bq/mg for uranium depleted to 0.2% in ^{235}U.

1.4. Elements of nuclear physics

Nuclear physics is the science concerned with all physical phenomena involving the atomic nucleus. Matter is made up of molecules, themselves made up of atoms. Atoms are made up of a central nucleus surrounded by electrons [BON 02].

In response to the approach of Rutherford, who in March 1911 sketched out the first model of the atom (a central electric charge concentrated in a point surrounded by a uniform spherical distribution of electricity of opposite sign in equal quantity), Bohr clarified on July 6, 1912, in a letter to Rutherford, that there could be no static equilibrium between the nucleus and electrons, and that the latter must therefore necessarily rotate. Moreover, a rotating ring is not stable for more than seven electrons, suggesting a structure of successive rings. He added that he saw a possible explanation for the periodic law of chemical properties of elements (assuming that chemical properties depend on the stability of the outermost ring, the "valence electrons"). A little later, Arnold Sommerfeld (1868–1951) clarified that if electrons obey classical mechanics in their orbits, they must describe *ellipses* with the nucleus as one of the *foci*.

After the question of the atom's structure, we will discuss the question of the nucleus with the discovery of the neutron in 1932. It was two German–Jewish

10 One milligram of natural uranium has an activity equal to 25 becquerels.

physicists, Walter Elsasser (1904–1991) and Kurt Guggenheimer (1896–1940), who took refuge in Paris[11] in 1933, who suggested that protons and neutrons could be *layered* in the nucleus, like electrons in the atom. Elsasser even specified that each particle, neutron or proton moves in an orbit, and that the particles must then be organized in successive layers, which he called envelopes.

The applications of nuclear physics, and in particular the use of the properties of ionizing radiation, are highly varied, in fields as diverse as astrophysics, archaeology (radioactive dating), medicine (radiology, radiotherapy, radioactive tracers), controlled energy production (electricity generation or nuclear propulsion) and uncontrolled energy production (military applications, bombs), food processing (food sterilization), chemical analysis by activation, non-destructive testing (search for anomalies in materials, constructions), conservation and restoration of objects, and cultural goods or archaeological remains[12] in organic materials (wood, leather, fibers) by gamma irradiation.

1.4.1. *Nuclear structure*

The atomic nucleus is made up of two types of nucleons[13], protons and neutrons. Protons are particles with a positive elementary electric charge, while neutrons are electrically neutral particles. Four elementary interactions, or fundamental forces, are responsible for all physical phenomena observed in the universe. These are strong nuclear interaction, electromagnetic interaction, weak nuclear interaction and gravitation. The strongest of these forces, strong nuclear interaction, holds nucleons together in the nucleus. The amount of energy that holds the nucleus together is called the binding energy of the nucleus.

When the number of protons in the nucleus is large, the Coulombic (or electromagnetic) interaction takes precedence over the strong interaction, and nuclei become unstable.

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11 Fleeing Nazi Germany like some 1,500 Jewish scientists, mostly in 1933, Elsasser obtained a position at the Centre de Recherches, forerunner of the CNRS, and Guggenheimer found refuge at the Collège de France, in Paul Langevin's laboratory. Many of these scientists (including James Franck, winner of the Nobel Prize in Physics in 1925) went into exile in the United Sates, where they took part in the Manhattan Project. Between 1937 and 1991, seven of them were awarded the Nobel Prize.

12 The mummy of Ramses II, which was attacked by various parasites, arrived in France (September 1976) for treatment by global gamma irradiation, carried out at the Centre d'études nucléaires de Saclay (May 1977), which destroyed the parasites.

13 Name given to protons and neutrons when we are interested in their similar characteristics: mass, spin, interactions between them. For example, deuterium has two nucleons: a proton and a neutron.

The number of protons in a nucleus defines its Z value (Figure 1.1). Nuclei with the same Z value, but different numbers of neutrons, are called isotopes. For nuclei naturally present in the universe, their mass number, A, varies from 1 to 238, and their atomic number, Z, from 1 to 92. The heaviest natural nucleus is uranium-238, composed of 92 protons and 146 neutrons, or 238 nucleons.

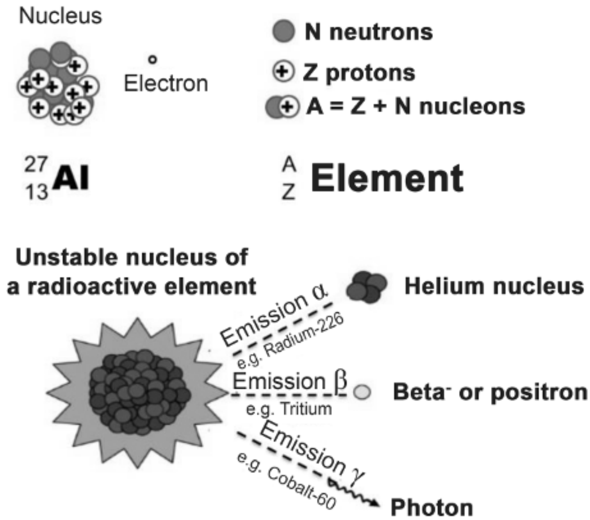

Figure 1.1. *Nuclear structure, symbolism and electrical charges of the three types of ionizing radiation. For a color version of this figure, see www.iste.co.uk/amiard/risk.zip*

The atomic mass unit (a.m.u.) is 1 dalton, or 1 g. (6.10)$^{23-1}$ or 1.667.10^{-27} kg. The mass of a proton is 1.6726.10^{-27} kg (or 1.0074 a.m.u.) and its charge is + 1.602.10^{-19} C. The mass of a proton is 1,836 times that of an electron. The mass of a neutron is very close to that of a proton (1.6748.10^{-27} kg or 1.0087 a.m.u.) and its charge is zero.

In 1931, the 27-year-old physicist Georges Gamow (1904–1968), a professor at the University of Leningrad, first put forward the idea that the atomic nucleus could be represented as a liquid drop. This liquid drop model is still one of the foundations of our understanding of the nucleus [FER 06, p. 263].

Just as the atom, thought to be unbreakable, was shown to be made up of protons, neutrons and electrons, physicists have also discovered that protons and neutrons, thought to be elementary particles, are themselves each made up of three quarks. As no substructure has yet been discovered at the level of quarks or electrons, quarks are the new elementary particles that make up the neutron and proton.

The matter that surrounds us, stable or almost stable, does not involve all these fermions[14], as some are only involved in extremely energetic processes. In fact, ordinary matter is made up of just three particles: protons, neutrons and electrons. The proton, an assembly of two u quarks and a d quark with a positive elementary electric charge ($1.602.10^{-19}$ Coulomb). The neutron, made up of one u quark and two d quarks, has a zero electric charge (hence its name, a reference to electrical neutrality). The electron is the lightest of the leptons and carries a negative elementary electric charge [NAU 08].

1.4.2. *Electrons*

Atoms are made up of a series of electrons orbiting in ellipses around a nucleus (one of the foci of the ellipses). These electrons are about 100,000 times smaller than the nucleus. They are tiny corpuscles with a negative electric charge e^- which is the smallest known electric charge. All observed electric charges are a positive or negative integer multiple of this charge e, which is called elementary.

The number of electrons in an atom ranges from one to almost a hundred (98 for ^{238}U). This defines the atomic number of the stable atom, which is equal to the number of protons Z. The electric charge of the electron cloud is exactly balanced by the sum of the positive electric charges present in the nucleus, due to the presence of protons, which carry an electric charge equal and opposite to that of the electron. In a stable atom, there are as many electrons as protons in the nucleus: it is therefore electrically neutral. The simplest atom is hydrogen, which has a single electron. The oxygen atom has 8.

Around a nucleus, electrons can only have a limited number of states. An electron’s state is characterized by its energy and the way it occupies space. Different states of the same energy are grouped together under the name of layers. An atom’s electrons belong to various layers characterized by energy. Atomists call these layers K, L, M, N, etc. The K layer corresponds to the strongest attraction to the nucleus. It is the first to fill up, and only two electrons can occupy this layer. A third electron must necessarily move to the next layer, the L-layer, where it will be less bound to the nucleus than its K-layer counterparts. The binding energies of the electrons on the subsequent layers become progressively lower. When a space becomes available on a more inner layer, an electron on an outer layer fills the gap

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14 A fermion is an elementary particle with bosons.

by jumping to occupy the space left free on this inner layer. It thus becomes more closely bound to the nucleus.

This transition of the electron from the L to the K layer is accompanied by the emission of an electromagnetic energy (E_X), which inherits the difference in binding energy between the two layers, reduced by the energy E_L required for the electron in the L layer to extract itself from its layer (i.e. $E_X = E_K - 2\,E_L$).

These tiny electromagnetic waves are called photons. For a given atom, the photon's energy is unique. Since the photon's wavelength is related to its energy, this wavelength is also unique. As a result, the photons emitted by an atom have energies that characterize it.

The outermost layers are responsible for the atom's chemical properties. This is illustrated by the vertical columns of Mendeleev's periodic table. The first column corresponds to alkalis with an outer layer possessing only one electron, the second column to alkaline earths with two electrons on the first outer sub-layer and the last column corresponding to rare gases where the second outer sub-layer is completed with its six electrons (Chelet, 1968).

When Z is equal to 2, 10, 18, 36, 54 and 86, the layers are complete and stability is maximum; these are the rare or noble gases [BAS 02]. Similarly, atomic nuclei seem to possess a layered structure, and can be built up, like atoms, by filling successive layers. This results in discontinuities with particular values for the number of neutrons N and protons Z called magic numbers (2, 8, 20, 50, 82 and 126, to which we must add 38 and 40) [BAS 02].

1.4.3. *Stability of the atomic nucleus and nuclear reactions*

According to Einstein's theory of special relativity ($E = m.c^2$ with E in joules, m in kilograms and c the speed of light[15], 3.10^8 $m.s^{-1}$), there is an equivalence between energy and mass, meaning that mass can be transformed into energy and vice versa. In the case of the helium nucleus, for example, its mass is 4.002 a.m.u., whereas the sum of the masses of two protons and two neutrons in isolation is 4.032 a.m.u., i.e. a difference of $0.03.10^{-3}$ kg for one mole of helium. The energy released in the formation of a helium nucleus is therefore $2.7.10^{12}$ $J.mol^{-1}$ $(0.03.10^{-3}).(3.10)^{82}$.

The energy released when a nucleus is formed depends on the number of associated nucleons. It is expressed in BEPN (binding energy per nucleon). It is minimal for lithium, then gradually increases to a maximum for ^{56}Fe (close to

15 According to the National Bureau of Standards, the most precise value for the speed of light in a *vacuum* is 299,792,456.2 ± 1.1 $m.s^{-1}$.

9 MeV), then slowly decreases for heavy nuclides. For helium, it is $1.12.10^{-12}$ J, or approximately 7 MeV. When measuring the kinetic energy of an electron, the unit used will be the electron volt (eV) rather than the joule (general unit), with 1 eV = $1.6.10^{-19}$ J or conversely 1 J = $6.25.10^{18}$ eV.

Core stability is achieved through three processes. For light nuclei, by nuclear fusion of two light nuclei; for heavy nuclei, either by radioactive decay, which takes place in stages, or by nuclear fission, which corresponds to the breakup of a heavy nucleus into two lighter nuclei. This mechanism is explained by the average BEPN expressed in million electron volts, MeV (Figure 1.2).

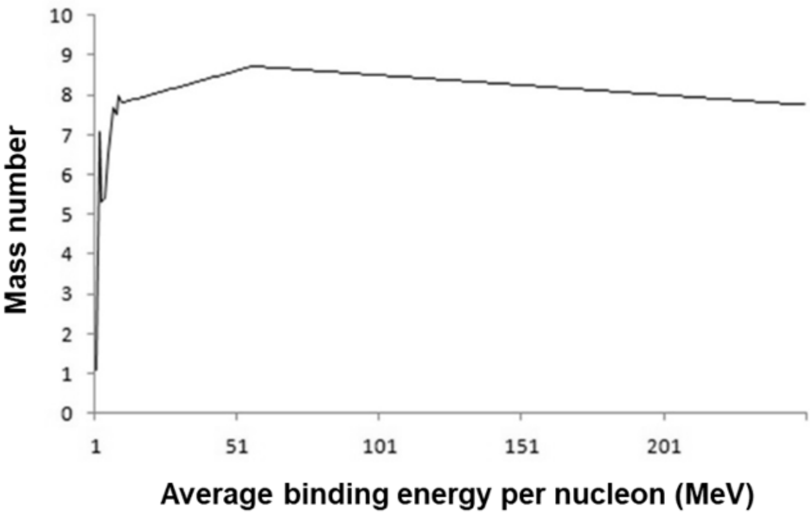

Figure 1.2. *Comparison of nuclide stability as a function of mass number and average binding energy per nucleon (MeV)*

A reaction is said to be nuclear when there is a change in the quantum state of the nucleus. The reaction involves not only the nucleons that make up the nucleus, but also other particles such as e^- electrons and e^+ positrons.

Nuclear reactions are varied. The main ones are fission, fusion and radioactivity.

Fission corresponds to a heavy nucleus breaking into two fragments. This is the type of reaction used in type A atomic bombs and nuclear power plants. Fission does not generally give rise to two identical isotopes. It is accompanied by the emission of neutrons[16], which maintain the chain reaction. The fission of uranium-235 by thermal neutrons, for example, produces strontium-90 and cesium-137 with high yields and half-lives of approximately 30 years.

Fusion occurs when several light nuclei fuse together. This is how stars produce energy. It is also the type of reaction used in so-called hydrogen bombs (H-bomb). The use of fusion for civilian energy production has not yet been mastered in the international project ITER (International Thermonuclear Experimental Reactor).

1.4.4. *Various types of ionizing radiation*

Radioactivity refers to a nucleus that emits one or more particles spontaneously. The type of radioactivity is defined by the particle emitted during the disintegration or transmutation of an atomic nucleus. There are four types of radioactivity and one mode of radiation:

i) α radioactivity, where a helium nucleus, formed of four nucleons, is emitted. This type of radioactivity concerns heavy nuclei (A>200) with an excess of nucleons. They lose four nucleons to stabilize. The Z is changed, resulting in the formation of a lighter chemical element. The alpha particle emitted along a straight trajectory is positively charged, and will be directly ionizing, with an increase in ionization density at the end of the trajectory (Bragg peak).

ii) β^- radioactivity, where an electron and an electron antineutrino are emitted. This type of radioactivity occurs in neutron-rich nuclei. A neutron is transformed into a proton, followed by the emission of an electron and an antineutrino. The electron emitted does not pre-exist in the nucleus, but is born from the transformation of a neutron in the nucleus. This electron or β^- particle is relativistic (emitted with a speed close to that of light) and its path through matter (several mm) is non-rectilinear. As the Z changes, this transmutation produces another chemical element.

iii) β^+ radioactivity, where a positron and an electron neutrino are emitted while a proton is transformed into a neutron. This type of radioactivity occurs in nuclei with too many protons. When the positron reaches the end of its path, it couples with an e^- electron, causing the two electrons to annihilate, followed by the formation of a pair of photons of 0.511 MeV (the electron's rest mass). As their momentum was zero, the two gamma photons were emitted in opposition. This mode of decay was discovered by physicist Lise Meitner. This property is used for medical imaging: positron emission tomography (PET scan).

16 In the case of fission of uranium-235 by thermal neutrons, an average number of 2.47 neutrons is produced. The average energy of these neutrons is 2 MeV [BAS 11, p. 66].

iv) Electron capture, which is a mode of nuclear decay that concerns nuclides with an excess of *protons*, and for which β^+ decay is impossible. During this decay, the neutron-deficient nucleus absorbs an electron from one of the atom's electronic layers. This operation leads to transmutation, because by incorporating the outer peripheral electron, the proton is transformed into a neutron and an electron neutrino is emitted. The atom's nucleus is modified, as it loses a proton and gains a neutron. The electron gap leads to the emission of X-ray photons in competition with Auger electrons.

γ emission is a de-excitation, not a decay. The daughter nuclei resulting from α, β^- or β^+ decay are very often in an excited energy state. They regain their *stable* ground state by emitting energy in the form of γ radiation. This is not material particle emission, but very high-frequency electromagnetic radiation ($f > 10^{18}$ Hz) which is far more penetrating of matter than alpha or beta particles.

The following example shows the decay scheme of cobalt-60 by β^- decay which leads to an excited nickel-60 level of 2.505 MeV. Two gammas, of 1.173 MeV and 1.332 MeV, are emitted to reach the stable nickel-60 level (Figure 1.3).

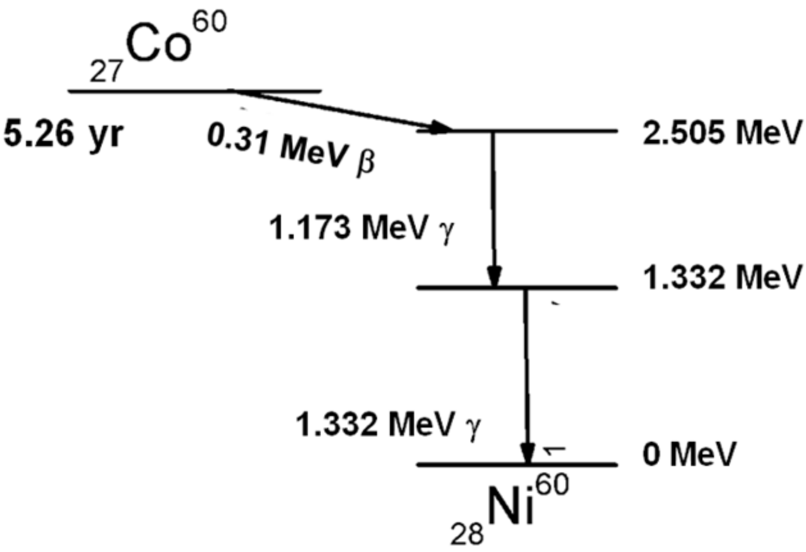

Figure 1.3. *Diagram of cobalt-60 decay*

A beam of radiation emitted by a radioactive source and subjected to an electric field created between two metal plates charged + and -, respectively, will cause a deviation in the beam's trajectory depending on the type of radiation. α rays, attracted by the - charged plate, are made up of positively charged particles. β rays, attracted by the + charged plate, are made up of negatively charged particles. γ rays, undeflected, are not made up of charged particles (Figure 1.1.). Depending on the type of radiation, the power to penetrate matter is very different (Figure 1.4.).

If we classify particles according to the length of their path through matter, alpha rays, with their rectilinear path[17], are the least penetrating, as the particle is heavy and ionizing, followed by β^- and β^+ electrons, which have a complex curvilinear path with energy cessions to other electrons present in matter, which then have their own trajectories. Gamma rays have the longest paths. The paths they take depend on the energy of the particles and the nature (density and z) of the materials they pass through. This conditions their paths in air or living matter (Tables 2.1 and 2.2).

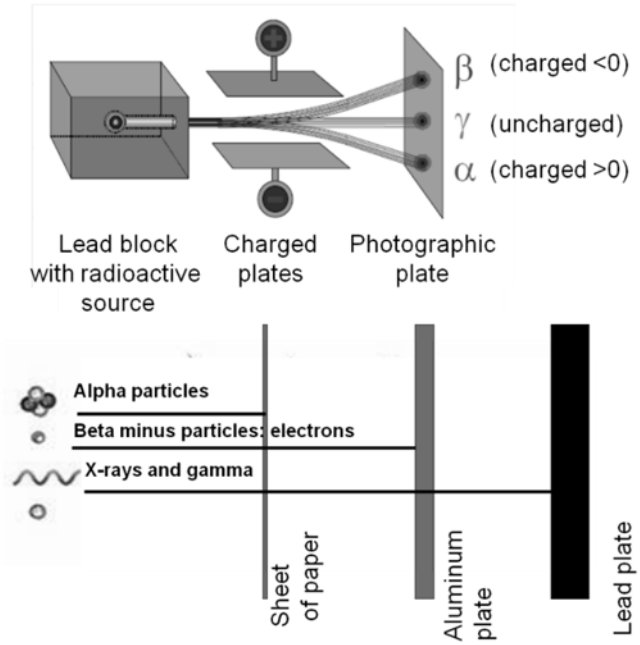

Figure 1.4. *The three types of ionizing radiation produced by nuclear reactions and the penetrating power of the various types of ionizing radiation. For a color version of this figure, see www.iste.co.uk/amiard/risk.zip*

17 Becquerel shows that the path of alphas is rectilinear, by making on a photographic plate, subjected to a beam of alphas, a very sharp image of a copper wire 1.5 mm in diameter [CUR 04, p. 85].

Type of radiation	Energy (MeV)	HLV (cm)
Gamma	6	16
Gamma (^{60}Co)	1.33	11
Gamma (^{137}Cs)	0.663	8.05

Table 1.1. *Half-layer values (HLV) in biological tissue*

Other types of ionizing radiation include particles emitted during beta+ decay and electron capture (positive electrons or positrons), and X-rays. X-rays and γ are the most energetic electromagnetic waves, which explains their ionizing power towards matter (Figure 1.5).

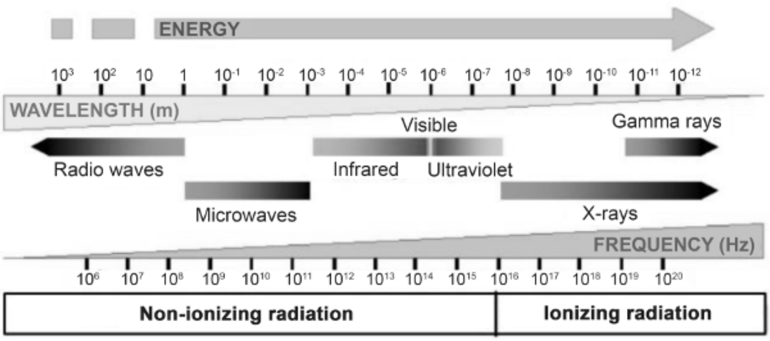

Figure 1.5. *Spectrum of electromagnetic waves. For a color version of this figure, see www.iste.co.uk/amiard/risk.zip*

1.4.4.1. *Alpha ionizing radiation*

The alpha particle is heavy, as it consists of four nucleons: two protons and two neutrons. It carries two positive charges, making it highly ionizing. The alphas emitted by emitting radionuclides are highly energetic, but within a relatively small energy range[18]; it extends from 4 to 9 MeV. Alpha decay occurs in heavier nuclei and concerns radionuclides with masses greater than 200[19]. Being heavy and positively charged, their mean free path is very short (on average 80 μm, i.e. about

18 The lowest alpha energy emitted by natural radionuclides is that of lead 210 (3.720 MeV, T = 22.23 years) and the highest is that of bismuth 214 (9.080 MeV, T = 19.8 min).
19 Tellurium-106 is often cited as the lightest isotope that undergoes alpha decay, but it is an artificial radionuclide with a half-life of 0.06 milliseconds.

twice the diameter of a cell), so they rapidly lose their kinetic energy at a short distance from the emission source.

In the event of internal contamination, alpha particles deliver high doses. Their capacity to cause harm is estimated at 20 times that of betas, X-rays and gammas.

In the event of external contamination, the alphas' path is, in most cases, too short to reach the basal layer of the epidermis. However, the risk of internal contamination persists in the case of irritated skin. Skin decontamination should therefore be carried out with mild soaps to avoid transcutaneous passages.

Accidental situations: the modes of contamination encountered in the workplace involve contaminated wounds or burns on the hand. A fraction remains locally fixed, but the remainder is rapidly absorbed into the circulating blood. In such cases, the victim must be injected with a chelating agent[20] adapted to the radionuclide in question, to speed up the natural elimination process. In the case of plutonium, the chelator used is DTPA[21].

1.4.4.2. *Beta ionizing radiation*

Beta radiation, emitted by a radioactive atom, consists of electrons with energies varying between zero and the maximum beta energy $E_{\beta max}$, which are emitted in 4π. The variability of the energy carried away by the electron results in a continuous spectrum of the distribution from zero to $E_{\beta max}$. The average energy of the electron spectrum $E_{\beta av}$ is approximately equal to one-third of the maximum beta energy $E_{\beta max}$. For a given electron in the energy spectrum, the complement to the maximum beta energy is carried away by the antineutrino. The antineutrino is an elementary corpuscle with no electric charge, virtually zero mass and very little interaction with matter.

Accidental situations: in some cases, contamination of the body can cause radiological burns. This was the case during the accident that occurred on the night of May 26, 1986 at Chernobyl reactor No. 4 (Ukraine). The firefighters, who came in light uniforms to extinguish the fire in the reactor's graphite mass, were heavily contaminated by combustion aerosols. Radiological burns, caused by the presence of a large number of fission products in the smoke and dust, severely aggravated their health situation, due to the severe external irradiation caused by the fuel in the

20 A chelator is a chemical substance that can take hold of a metal and form a stable, inert complex, which can be eliminated from the body much more quickly than the toxic metal.
21 DTPA = diethylene triamine penta-acetic acid.

reactor core, which had been stopped but virtually laid bare by the energies delivered by the enormous power spike[22] and the ensuing explosion.

1.4.4.3. *Gamma ionizing radiation*

Gamma radiation is composed of high-energy photons. This radiation will penetrate more matter and the body than alpha and beta radiation. There are three types of interaction between gamma rays and matter, depending on their energy: the photoelectric effect, the Compton effect and pair formation (two 0.511 MeV photons are formed). In the case of the photoelectric effect and pair formation, the incident photon disappears.

The photoelectric effect, which predominates at low X and gamma energies, takes place between the incident photon and a K or L layer electron. This requires the photon energy to be equal to or greater than the binding energy. The electron is ejected with an energy equal to the energy of the incident photon minus the binding energy. A rearrangement of the electron pattern ensues, with the emission of X-rays and/or Auger electrons.

The Compton effect also takes place between the incident photon and an electron of the K or L layer. The incident photon tears an electron from its layer, imparting energy to it, while the photon is scattered with an energy reduced by the binding energy (E_K or E_L) and the kinetic energy transferred to the electron. The energy of the scattered photon depends on the energy of the incident photon and the scattering angle. For incident energies of a few tens of keV, the energy transferred to the electron is low. Table 1.2 gives the kinetic energy carried away by the electron and that of the photon scattered at an angle of 90° to the incident photon.

Radionuclide	**Eγ of the incident photon (keV)**	**Compton electron energy (keV)**	**Eγ of the scattered photon (keV)**
^{125}I	27.5	1.4 (5.1%)	26.1
^{99m}Tc	141.0	30.5 (21.6%)	110.5
^{131}I	364.0	151.4 (41.6%)	212.6
^{60}Co	1.332	961.0 (72.1%)	369

Table 1.2. *Energy of the Compton electron and the photon scattered at 90° (according to [GAM 97, p. 61]). Note: in brackets, fraction of energy transferred to the electron*

22 Calculations have shown that the reactor's instantaneous power would have reached 100 times its nominal value in four seconds [LIB 96, page 313].

Table 1.2 shows that at low incident photon energies, the kinetic energy imparted is low, resulting in a scattered photon with low attenuated energy. The higher the incident photon energy, the higher the energy transfer to the electron: 5.1% for photons of 27.5 keV and 72.1% for 1.332 MeV. For incident photons of a few tens of keV, the scattered photon's energy is only slightly reduced, enabling multiple scattering. A cloud of scattered photons then surrounds the target. At energies in excess of 1 MeV, Compton electrons are predominantly scattered forward, and the angle of the scattered photon cone is reduced. This is why radiotherapy treatments are carried out using high-energy photons (approximately 5 MeV).

Radionuclide (period)	**Gamma energy in keV (emission rate)**	**Dose rate mSv/h for 1 GBq at 1 meter**	**Lead thickness in cm for a 95% attenuation**
Chromium-51 (27,703 days)	320.08 (9.87%)	$6.32.10^{-3}$	0.78
Cesium-137 (30.05 years)	661.66 (84.99%)	0.102	2.45
Cobalt-60 (5.2711 years)	1,173.2 and 1,332.5 (99.85% and 99.98%)	0.37	4.41

Table 1.3. *Dose rate and photon attenuation of a gamma point source*

Table 1.3 shows the dose rates delivered by gamma photons of increasing energy, emitted by point sources of radionuclides [AIR 12]. Energy transfer is achieved by the photoelectric and Compton effects for chromium-51 and cesium-137. For cobalt-60, the pair-forming effect is partially added to the other two effects. Dose rates, along with the lead thicknesses needed to attenuate 95% of the γ emitted, increase with photon energy.

Pair formation is only possible for incident photons of energy $E\gamma \geq 1.02$ MeV. In the electric field of the nucleus, the photon disappears, giving a negative electron and a positive electron (positron). The conservation of electric charge is respected (as the photon has no charge), as is that of energy. The difference in energy ($E\gamma$ -1.02 MeV) is shared between the electron and the positron in the form of kinetic energy. At the end of its path, the positron couples with an electron, and their annihilation produces two 0.511 MeV photons, emitted in phase opposition (momentum being zero at the end of the path).

Accidental situations: these occur in a number of scenarios, including sealed radioactive sources which accidentally become disconnected from a portable irradiator. Found by chance and picked up by a member of the public, who puts it in their pocket, where it remains for several hours. This type of exposure can result in one or more amputations [AMI 19, ZER 94]. More serious, however, is the case where the person leaves the source at home, since exposure times are no longer measured in hours, but in days and sometimes weeks. The discovery of the source usually follows the nausea and vomiting of family members. In these situations, fatal injuries are also reported (28 deaths listed by Amiard for 1968–2002) [AMI 19, pp. 195–202].

In addition to these exposures of members of the public, there are also cases, generally very serious, of exposure of professionals who enter an irradiation room while the sources or the gas accelerator beam are in irradiation position [AMI 19, pp. 206–210, ZER 93, ZER 94].

1.4.4.4. *Neutrons*

The neutron is not electrically charged, so it does not produce ionizations as it passes through matter. It only interacts with a nucleus, but as the latter occupies a very small volume in the atom, this limits interactions. A neutron flux can therefore be extremely penetrating. Free neutrons do not therefore directly form ionizing radiation, but by provoking nuclear interactions, they can generate ionizing particles (gammas). When a neutron interacts with a nucleus, it usually bounces back, and in a few cases is incorporated into the nucleus. This neutron reaction increases the mass of the target nucleus by one, producing a transmutation that creates a radionuclide. In the case of a heavy nucleus, this neutron integration produces an unstable nucleus that fissions into two unequal parts, emitting neutrons. In the case of uranium-235, the capture of a neutron by the nucleus produces uranium-236, which fissions rapidly, producing two fission products and two or three fast neutrons (2.47 on average). These neutrons keep the nuclear reaction under control in a reactor, but in certain accidental conditions, they can produce a powerful neutron flash that delivers a lethal dose up to several meters away. To stop the neutrons, protective shields rich in hydrogenated materials such as water (H_2O), graphite (C) or kerosene (C_nH_{2n+2}) are used. Neutron activation can be used to analyze chemical composition or detect impurities in a material.

Accidental situations: cases of accidental neutron irradiation only occur in the professional world. They occur when two metallic masses of plutonium or enriched uranium are mistakenly brought together, thus reaching and then exceeding the critical mass[23] for this material, or when a container is poorly controlled and filled with one of these fissile materials. If the source is in liquid phase, the dose delivered is lethal within a radius of approximately 8 m from the source. In the solid phase,

23 Mass of fissile material nuclei required for a chain reaction to produce neutrons equal to the number of neutrons absorbed.

this radius is increased to 12 m. In addition to the neutron dose, a gamma dose is produced by activation reactions in the victim's body and environment.

Since 1945, there have been 60 accidents worldwide, of which only six occurred after 1978. The first victim was a 24-year-old physicist, Harry Daghlian, associated with the Manhattan program, who two weeks after the bombing of Hiroshima on August 6th, inadvertently brought together two masses of plutonium metal. The critical mass was reached, and the critical excursion, with its neutron flash, led to his death 20 days later, in excruciating pain [BER 22, p. 185]. The last three accidents took place in Japan, at the Tokai-Mura site. On September 30, 1999 at Tokai-Mura, a criticality accident occurred in a uranium processing plant where a neutron safety procedure had not been observed. An excessive quantity of enriched uranyl nitrate was poured into a tank instead of a safe geometry dissolver. This accident caused severe global irradiation syndrome[24] in three workers, resulting in the death of one of the victims despite 83 days of intensive care [IRS 00]. It should therefore be noted that the mortality risks associated with criticality accidents are high. Depending on the author, they range from 17 to 20, i.e. almost one death for every three accidents [AMI 19, pp. 14 and 15].

In the absence of individual dosimetry, biological dosimetry is applied, using gamma spectrometry to measure the ^{24}Na produced by activation (n,γ) of ^{23}Na, the stable sodium present in blood. In order to determine the angular position of the victim during the fast neutron flash, the victim's skin (nails, hair) is sampled for sulfur, which produces phosphorus-32 (^{32}P) by reaction (n,p[25]) with the isotope ^{32}S, the majority being sulfur (i = 95.3%). The activities induced in the skin make it possible to determine the angle the person was at, in relation to the incident neutron beam. This data is useful for calculating the dose, or for reconstructing the accident using a Phantom[26] equipped with dosimeters. The rate of chromosomal abnormalities can also be used to assess the dose received.

1.4.4.5. *Cosmic radiation*

In 1897, physicist Charles Wilson (1869–1959) discovered with his apparatus that about 20 ions per second are formed in 1 cm^3 of air, regardless of the location. He assumed that this ionization could be caused by sources outside the atmosphere. Rutherford (1871–1937) confirmed these results in 1902.

24 The Tokai-Mura Center estimated that the three operators had received approximately 9 grays (Gy), approximately 5 Gy and just over 1.2 Gy, respectively [IRS 00].

25 n = neutron, p = proton.

26 An anthropomorphic mannequin, made up of a human skeleton encased in a plastic material equivalent to human tissue. It takes the form of a stack of 1-inch-thick (25.4 mm) slices pierced by small blind holes into which FLi dosimeters are inserted. All the point doses measured are used to assess the dose to organs and calculate the effective dose received by the exposed victim.

Since the discovery made by Austrian physicist Viktor Franz Hess (1883–1964) on August 7, 1912, when he measured the rate of air ionization (number of ions created per second and per cm^3 of air) as a function of altitude, a number of studies have been carried out to discover the exact nature of these cosmic rays, which propagate at speeds close to that of light.

In 1938, French astronomer Pierre Auger (1898–1993) discovered that the penetration of particles into the Earth's atmosphere, which collide with the oxygen and nitrogen in the air[27], triggers large "sheaves of particles", which are secondary particles in contrast to primary particles of cosmic origin. The vast majority are atomic nuclei, positively charged heavy ions. Virtually all chemical elements are represented, from hydrogen to iron and beyond, but at lower intensities. The intensity of this radiation depends on latitude (intensity increases closer to the poles) and altitude. As altitude increases, the layer of air protecting us from this radiation decreases.

1.4.4.6. *Auger electrons*

Their penetration is identical to that of electrons of the same energy. Auger electrons are mono-energetic electrons, emitted after a rearrangement of peripheral electrons, caused by the disappearance of a K-layer electron. This non-radiative transition phenomenon, which competes with the emission of X-ray lines, was discovered and published in 1923 by Lise Meitner, but it was Pierre Auger, who also became interested in the phenomenon a few years later, who gave it its name.

1.4.5. ***Radiation properties***

The two main properties of radiation are its power to penetrate matter and ionizing power (Table 1.3). Radiation thus has a greater or lesser tendency to penetrate obstacles placed in its path. This penetration power depends on the nature of the radiation, with α emissions penetrating very little and γ rays penetrating a great deal. Ionizing power translates into a greater or lesser degree of ionization of the material traversed along the path of the radiation. Under the impact of collisions, certain atoms lose electrons and are transformed into cations, and these stripped electrons are captured by other atoms.

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27 It is these secondary particles that produce carbon-14, the radioactive isotope of the long-lived element carbon (5,700 years), by interacting with nitrogen in the air (mainly with the nitrogen-14 isotope, which makes up the majority of the element nitrogen, chemical symbol N).

Capacity	α rays	β rays	γ rays
Penetration power	Very weak. All radionuclide alphas are stopped by 10 centimeters of air or a thin sheet of paper.	Quite large. All β rays from radionuclides can be stopped by a 12 mm plate of Plexiglass*.	Very large. To stop 95% of γ rays from all radionuclides, an 8-centimeter lead shield is required.
Ionizing power	Very high	Significantly lower than α	Weak compared to β rays

*To stop β-radiation, it is best to choose a screen with a low atomic mass, because as electrons slow down in matter, they produce braking gamma radiation (*Bremsstrahlung*). The intensity of this γ-radiation increases with the atomic mass of the screen.

Table 1.4. *Penetration and ionization power of various types of radiation*

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